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Resonant light induced mechanical interaction between a pair of quantum dots

— 量子ドット対の間に生じる共鳴光誘起力学的相互作用 —

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Abstract

微視的光学応答理論に基づき、自由空間に浮遊する複数の QD に共鳴光を照射した場合に生じる輻射力の解析的表式を導出し、その本質的な性質について議論する。この表式の応用例として、まずは 2 個の近接する QD を対象に調べた。結果として、2 個の QD 中に生じる『ポラリトニック分子』の結合・反結合状態を異なる偏光で励起した時に引力・斥力が生じることを示した。これらの考察は、将来的には、「光による量子ドットの集団運動の制御」に繋がると考えられる。

1.Introduction

The radiation force (RF) arising from the light-matter mechanical interaction is utilized in the optical manipulation to control the mechanical motion of small objects floating in the fluid medium [1]. Previously, we have theoretically studied the RF exerted on a single quantum dot (QD) confining excitons under a resonant light irradiation [2], and proposed a new type of optical manipulation for sorting out QDs with particular size, shape and quality. On the other hand, many researchers are engaged in studies about the properties of the electronic systems confined in the quantum dots (QDs). They often call a QD an 'artificial atom' because of its discrete electronic excitation levels like those of a real atom. Recently, it has been reported that the coherent coupling and entanglement of electrons in two QDs, and this system is called an 'artificial molecule' [3]. In the experiment, QDs embedded in the layer-structured semiconductor are used, and the excitation of coupled states of a QD-pair is not linked with the mechanical motion of QDs. However, if the target QDs are floating in the fluid medium, such a situation greatly affects the relative motion of QDs. In order to clarify the linkage between the coherent coupling of QDs and RF, we derive the analytical expression of the RF in terms of the microscopic response field, and numerically evaluate the RF between a pair of QDs with this expression.

2.Results and Discussions

Substituting the response field calculated by 'Microscopic Nonlocal Theory' [4] into the expression of time-averaged Lorentz force, we derive the analytical expression of the RF exerted on plural nano objects under an electronic resonant light irradiation. Applying this expression to plural spherical QDs confining excitons, we calculate the RF between QDs under the assumption that each QD has degenerate excitation levels with transition dipole densities $\vec{\rho}_{i\xi}(\mathbf{r})$ directed to a unit vector $\vec{\xi}(=\hat{x},\hat{y},\hat{z})$. When the object is much smaller than the wavelength of light, the Mie resonance frequencies, which arises from the contribution of background dielectric constant, shift to higher energy beyond the usual laser frequency region. Therefore, we can neglect the RF exerted on the nonresonant induced polarization. Thus, the RF exerted on the resonant induced polarization $\mathbf{P}_i(\mathbf{r},\omega)=\Sigma_\xi X_{i\xi}(\omega)\vec{\rho}_{i\xi}(\mathbf{r})^*$ in the ith QD is described as

$$\langle\mathbf{F}\rangle_i=\frac{1}{2}\sum_{\xi}\mathrm{Re}[X_{i\xi}(\omega)\int_{V_i}d\mathbf{r}(\nabla\mathbf{E}^{(b)}(\mathbf{r},\omega)^*)\cdot\vec{\rho}_{i\xi}(\mathbf{r})^*+\sum_{j,\eta}X_{i\xi}(\omega)X_{j\eta}(\omega)^*[\nabla_{ij}A_{\xi\eta}(\mathbf{r}_{ij},\omega)^*]\Big], \quad (1)$$

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where $A_{\xi\eta}(\mathbf{r}_{ij},\omega)$ is the interaction between transition dipoles in different QDs via electromagnetic field with both longitudinal and transverse components as a function of relative coordinate of QDs $\mathbf{r}_{ij}$, and $X_{i\xi}$ is a coefficient of the induced polarization of (i,ξ)-exciton level with a resonant denominator including an eigenenergy corrected by $A_{\xi\eta}(\mathbf{r}_{ij},\omega)$. In r.h.s. of Eq.(1), the 1st term is RF on ith QD by the incident field $\mathbf{E}^{(b)}$, and the 2nd one is the sum of RF on ith QD by induced fields from all QDs. The 1st term corresponds to the dissipative force (as a sum of scattering and absorbing forces by light with a momentum in a propagating direction) and the gradient force (by light with inhomogeneous intensity like standing wave etc.) as discussed in the case of a single QD [2].

In Fig.1-(b), we numerically evaluate respective components of the acceleration a_x and a_y on QD $\langle 1\rangle$ by $\langle\mathbf{F}\rangle_1$ when two QDs are aligned in y-direction and irradiated by a plane wave propagating in x-direction as shown in Fig.1-(a). a_x and a_y correspond to the 1st term and 2nd one in r.h.s. of Eq.(1), respectively. $|a_x|$ and $|a_y|$ for QD $\langle 2\rangle$ are the same as those for QD $\langle 1\rangle$, but the sign of a_y is opposite due to the symmetry. a_z is zero for both QDs. Parameters of CuCl Z_3 exciton are used, but the background dielectric constant is assumed to be unity in order to discuss the essential properties of the resonant RF. The considered laser intensity is within the linear response regime for the calculated radiative decay constant (about 50 μeV) and the assumed nonradiative damping parameter $\gamma = 2$ μeV (this γ can be obtained in the cryogenic condition such as in the superfluid helium-4). For the distance $d = 41$ nm, we can see that the peak position of a_x (a_y) moves to lower energy for y-polarization (bonding state), and to higher energy for z-polarization (antibonding state), which is determined by the resonance structure of $X_{i\xi}$. Such a shift of eigenenergy is similar to that of bonding and antibonding states of a real hydrogen molecule. However, we call this system 'polaritonic molecule' because the light-matter coupled states (polaritons) are coherently coupled via radiation but not via overlap of the electronic wavefunctions. The attractive and repulsive RFs arise between a QD-pair when the bonding and antibonding states are optically excited, respectively, which is determined by the sign of the interaction gradient $\mathrm{Re}[\nabla_{ij}A_{\xi\eta}(\mathbf{r}_{ij},\omega)^*]$. Particularly, even for the assumed laser intensity within the linear response regime, the magnitude of these forces becomes several ten-thousands times as large as the gravitational one (9.8 m/sec^2). Since these repulsive and attractive RF can be maintained in an optical potential well, we can control the relative motion of trapped QD-pairs. The discussion in this contribution would open the way to control the collective motion of many QDs under resonant light irradiation.

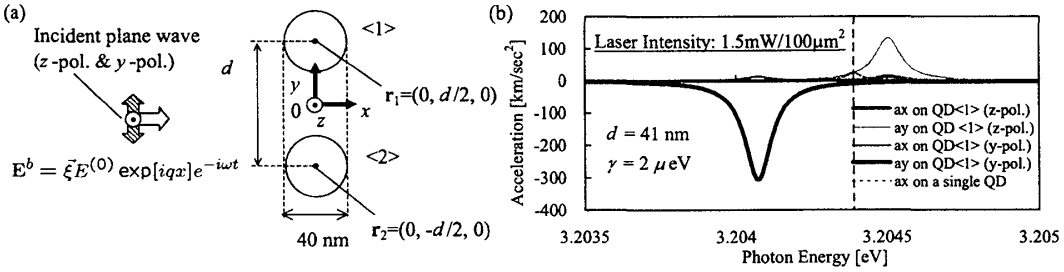

Figure 1: (a): Geometry of the model for the calculation. (b): Optical frequency dependence of the acceleration (force normalized by mass of a single QD) induced by RF exerted on QD $\langle 1\rangle$ for z- and y-polarization. The acceleration on a single QD is shown together (dotted line). The broken line indicates the peak position of the acceleration on a single QD.

References

[1] A. Ashkin, et. al., Opt. Lett. **11**(1986),288; D.G.Grier, Nature **424**(2003), 810.
[2] T.Iida and H. Ishihara, PRL. **90** (2003), 057403; See also PR Focus, Story 6, 11 Feb.
[3] M. Bayer, et. al., Science **291**(2001), 451.
[4] K.Cho, "Optical Response of Nanostructures" (Springer,2003).